Fermi National Accelerator Laboratory

FN-494

Shielding the TEVATRON Bellows

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September 1988

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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I. INTRODUCTION

The bellows of the Fermilab Main Ring are shielded. The coupling impedance is greatly reduced so that the bunches can be made more stable when the rf voltage is lowered in the process of bunch coalescence. The Superconducting Super Collider (SSC) is also designed with the bellows shielded so that the bunches are stable against transverse microwave (fast head-tail) instability. The question of whether the Tevatron bellows should also be shielded is naturally raised.

II. THE TEVATRON BELLOWS

There are about 1000 bellows in the Tevatron.[1] Each has a length of 4.59 cm consisting of 24 ripples and an average radius of 4.26 cm, joined onto beam pipes of radius 3.49 cm. The ripples have depths of 0.77 cm. This is illustrated in Fig. 1. These dimensions are measured at a room temperature of ~ 300 K. During operation, the stainless steel beam pipe and the bellows are at helium temperature of 4.2 to 4.3 K. The thermal expansion for stainless steel is 14.5×10^{-6}/K. The total contraction in circumference of the 1 km ring is therefore 2690 cm, or 2.69 cm per bellows. Thus, the peak or valley of each ripple has an average width of $(4.59 + 2.69)/47 = 0.155$ cm.

Bellows can be classified into two extreme types. One is inner bellows where the average radius is the same as that of the beam pipe. The impedance is contributed from the electromagnetic fields residing inside the ripples. The result is a broad-band impedance. The position and peak value of the broad band can be estimated empirically.[2] The impedance at low frequency is just the impedance due to a step into the ripple depth and can be computed easily. The Fermilab accumulator has this type of bellows. The other type of bellows consists of a large cylindrical pill-box cavity having a radius and length roughly twice that of the beam-pipe radius. There are only a few ripples in the cavity wall. Here, the impedance is dominated by that of the cavity and the effect of the ripples is negligible. Thus, the impedance consists of narrow resonances of the cavity, and it can be estimated.[3] The low-frequency behavior is the result of the step into the cavity. The Fermilab Booster and Main Ring were built with this type of bellows.

As shown in Fig. 1, the Tevatron bellows are something in between. If we considered them as pill-box cavities, they are very shallow pill-boxes. As a result, the impedance will not be dominated by either the pill box alone nor by the ripples alone. A TBCI run[4] is therefore necessary. To facilitate the computer run, the dimensions of the bellows at cryogenic temperature are altered slightly as shown in Fig. 1(b).

The mesh size used is 0.3 mm and a length of wake of 1.40 m is computed. The longitudinal and transverse wakes for one bellows consisting of 24 ripples are shown in Figs. 2(a) and (b) respectively. Their Fourier transforms, the longitudinal impedance and the transverse impedance are shown, respectively, in Figs. 3 and 4.

Either the longitudinal impedance or the transverse impedance shows a broad band around ~ 7 GHz bisected by narrow resonances. The broad band is clearly the contribution of the ripples, but the resonances are from the shallow cavity. The cutoff frequency is 3.0 GHz. The resonances, broad band, and the impedance at zero frequency are listed in Table I for the longitudinal case and Table II for the transverse case. We see that the narrow resonances have rather small figures of merit. This may be due to the fact that the resonant fields cannot be trapped in the shallow cavities.

	f_r (GHz)	$Z_{\parallel\rm sh}$ (kΩ)	Q	$Z_{\parallel\rm sh}/n$ (Ω)	$Z_{\parallel\rm sh}/Q$ (kΩ)
Resonance 1	2.95	50.0	34	0.809	1.5
Resonance 2	3.65	74.1	8.8	0.970	8.4
Resonance 3	6.45	191	74	1.42	2.57
Resonance 4	7.41	191	85	1.23	2.24
Broad band	7.29	86.2		0.563	
$\mathcal{I}m\, Z_\parallel/n$ at zero freq $= 0.450\ \Omega$					

Table I: Longitudinal impedance for 1000 bellows. The resonant position, shunt impedance, and figure of merit are denoted by f_r, $Z_{\parallel\rm sh}$, and Q respectively.

III. INSTABILITIES

Since the narrowest resonance of the bellows has a full-width-at-half-power of ~ 0.17 GHz, it has a wake of characteristic length $1/0.17\pi = 1.9$ ns. The Tevatron buckets are separated by 18.8 ns. Therefore, even if all buckets were occupied, the

	f_r (GHz)	$Z_{\perp\mathrm{sh}}$ (MΩ/m)	Q	$Z_{\perp\mathrm{sh}}/Q$ (MΩ/m)
Resonance 1	2.33	0.816	22	0.037
Resonance 2	4.93	1.02	30	0.034
Resonance 3	5.66	1.27	25	0.051
Resonance 4	6.59	1.39	27	0.051
Resonance 5	7.52	1.86	72	0.025
Broad band	6.41	0.816		
$\mathcal{Im}\, Z_\perp$ at zero freq = 0.500 MΩ/m				

Table II: Transverse impedance for 1000 bellows. The resonant position, shunt impedance, and figure of merit are denoted by f_r, $Z_{\perp\mathrm{sh}}$, and Q respectively.

bellows would not induce any coupled-bunch motion. As a result, we will analyse single-bunch collective motions only.

To safeguard against fast longitudinal microwave instability and transverse microwave (fast head-tail) instability, we must have[5]

$$\left|\frac{Z_\parallel}{n}\right| < \frac{2\pi|\eta|(E/e)\delta_E^2}{I_p} \,, \tag{3.1}$$

and

$$|Z_\perp| < \frac{4\sqrt{2\pi}|\eta|(E/e)\delta_E n}{I_p\bar{\beta}} \,, \tag{3.2}$$

for a broad-band impedance having a width bigger than the spectral width of the bunch. In the case of a narrow resonant impedance with a width narrower than the spectral width of the bunch, the stability conditions become[6]

$$\frac{Z_{\parallel\mathrm{sh}}}{Q} < \frac{4|\eta|(E/e)\delta_E^2}{I_{\mathrm{av}}} \,, \tag{3.3}$$

and

$$\frac{Z_{\perp\mathrm{sh}}}{Q} < \frac{8\sqrt{2/\pi}|\eta|(E/e)\delta_E}{I_{\mathrm{av}}\bar{\beta}} \ . \tag{3.4}$$

For safeguard against coupled-bunch-mode or mode-colliding instabilities, we must have[5]

$$\left|\frac{\bar{Z}_{\parallel}}{n}\right| < \frac{8\pi|\eta|(E/e)\delta_E^2}{I_{\mathrm{av}}}\frac{\sigma_\ell}{R} \ , \tag{3.5}$$

and

$$\left|\bar{Z}_{\perp}\right| < \frac{4\sqrt{\pi}|\eta|(E/e)\delta_E}{I_{\mathrm{av}}\bar{\beta}} \ . \tag{3.6}$$

In above, $I_p = eNc/\sqrt{2\pi}\sigma_\ell$ is the peak current of the bunch containing N particles of charge e and rms length σ_ℓ, while $I_{\mathrm{av}} = eNc/2\pi R$ is the average current of one bunch with R denoting the radius of the Tevatron and c the velocity of light. Also η is the frequency-flip parameter, δ_E is the rms fractional energy spread, and $\bar{\beta}$ is the average beta-function. The n in Eq. (3.2) is the harmonic number of peak of the broad band. The *average* longitudinal and transverse impedances in Eqs. (3.5) and (3.6) are defined as

$$\bar{Z}_{\parallel} = \frac{\sqrt{\pi}c}{\sigma_\ell}\int_{-\infty}^{\infty} d\omega Z_{\parallel}(\omega)e^{-(\omega\sigma_\ell/c)^2} \ , \tag{3.7}$$

and

$$\bar{Z}_{\perp} = \frac{\sqrt{\pi}c}{\sigma_\ell}\int_{-\infty}^{\infty} d\omega Z_{\perp}(\omega)e^{-(\omega\sigma_\ell/c)^2} \ . \tag{3.8}$$

We take the data:

$$\begin{aligned} \eta &= 0.0028, \\ N &= 1.0 \times 10^{11} \text{ per bunch}, \\ \sigma_\ell &= 20.4 \text{ cm}, \\ \text{rms bunch area} &= 0.50 \text{ eV-sec}, \\ \bar{\beta} &= 50 \text{ m}. \end{aligned}$$

Thus, we get for the peak current $I_p = 9.40$ A and the average bunch current $I_{\mathrm{av}} = 7.65 \times 10^{-4}$ A. The rms fractional energy spread is

$$\delta_E = \begin{cases} 1.56 \times 10^{-3} & \text{at injection (150 GeV)} \\ 2.34 \times 10^{-4} & \text{at storage (1 Tev) .} \end{cases}$$

The numerical values of the thresholds are given in Table III.

Comparing Tables I and II with Table III, we see that the contributions of the bellows are less than 1% to 2% of the thresholds in all cases, independent of whether

Instability	Longitudinal Threshold	Transverse Threshold
Microwave (150 GeV)	$\lvert Z_\parallel/n\rvert = 638\ \Omega$	$\lvert Z_\perp\rvert = 96.6\ \mathrm{M}\Omega/\mathrm{m}$
	$Z_{\parallel_{\rm sh}}/Q = 0.12\ \mathrm{M}\Omega$	$Z_{\perp_{\rm sh}}/Q = 109\ \mathrm{M}\Omega/\mathrm{m}$
Microwave (1 TeV)	$\lvert Z_\parallel/n\rvert = 103\ \Omega$	$\lvert Z_\perp\rvert = 96.6\ \mathrm{M}\Omega/\mathrm{m}$
	$Z_{\parallel_{\rm sh}}/Q = 0.80\ \mathrm{M}\Omega$	$Z_{\perp_{\rm sh}}/Q = 109\ \mathrm{M}\Omega/\mathrm{m}$
Mode-coupling (150 GeV)	$\mathcal{I}m(\bar{Z}_\parallel/n) = 3610\ \Omega$	$\mathcal{I}m(\bar{Z}_\perp) = 121\ \mathrm{M}\Omega/\mathrm{m}$
Mode-coupling (1 TeV)	$\mathcal{I}m(\bar{Z}_\parallel/n) = 580\ \Omega$	$\mathcal{I}m(\bar{Z}_\perp) = 121\ \mathrm{M}\Omega/\mathrm{m}$

Table III: Impedance Thresholds for Microwave and Mode-Coupling Instabilities at 150 GeV and 1 TeV

the sharp resonances are wider or narrower than the spread of the bunch spectrum. It is not probable that the bunch area will be made smaller than 3.0 eV-sec (95%) and the number of particle per bunch will be made larger than 1.0×10^{11}. Thus, it appears that there is no need to shield the bellows.

One may wonder why the Main Ring bellows and the SSC bellows need shieldings but the Tevatron bellows do not need any. First, the impedance contribution of the Main Ring bellows[3] comes mainly from the very sharp resonances of the big bellows pill-boxes with $Q \sim 5000$, giving a $Z_{\parallel_{\rm sh}}/Q \sim 37$ kΩ. These resonances can lead to collective coupled-bunch motions. Ordinarily, the microwave instability threshold is $Z_{\parallel_{\rm sh}}/Q \sim 300$ kΩ, which is not small at all. However, there are a lot of rf maneuverings in the Main Ring, for example, the preparation of the proton bunch for antiproton production and the coalescence of the proton bunches and that of the antiproton bunches for injection into the Tevatron. During these maneuverings, the rf voltage needs to be lowered adiabatically so that the bucket area becomes equal to the bunch area. The fractional energy spread will therefore be lowered to a small value. To safeguard the bunch, against microwave stability, the threshold is lowered[3] to $Z_{\parallel_{\rm sh}}/Q \sim 9.5$ kΩ. Thus, the Main Ring bellows need to be shielded.

It is shown in Ref. 2 that for the broad band of an inner bellows, the peak impedances vary as

$$\left|\frac{Z_\parallel}{n}\right| \propto \frac{\ell\Delta}{b} \,, \tag{3.9}$$

$$|Z_\perp| \propto \frac{\ell\Delta}{b^3} \,, \tag{3.10}$$

where b is the beam pipe radius, Δ is the depth of the ripple, and ℓ is the total length of bellows required. At low frequencies, $\mathcal{Im}\,\bar{Z}_\parallel/n$ and $\mathcal{Im}\,\bar{Z}_\perp$ also have the same variations. The SSC is a very big machine running at cryogenic temperature. Therefore ℓ is very big. Also, in order to minimize the cost, a very narrow beam pipe of $b \approx 1.5$ cm has been chosen. Thus, the transverse impedance becomes very big. In fact, such a big machine is more dangerous to transverse microwave instability than the longitudinal one. Thus, shielding of the bellows is recommended in order to reduce the transverse coupling impedance. The Tevatron is very different. It is smaller than the SSC, the beam pipe radius is bigger, the frequency-flip parameter is bigger ($\eta = 0.00023$ for the SSC), the energy is smaller, and also the bunch area is bigger (rms bunch area for the SSC is 0.035π eV-sec at injection). All these factors contribute to the rather large instability thresholds for the Tevatron.

REFERENCES

1. K.Y. Ng, Fermilab Report UPC-150 (1981), where the longitudinal impedance of the bellows is estimated by replacing each ripple by a radial waveguide and also without consideration of the bellows expansion due to cryogenic temperature. The estimation in the present paper is much better.

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4. T. Weiland, DESY 82-015, 1982.

5. see for example R. Ruth, *Accelerator Physics Issues for a Superconducting Super Collider*, Ann Arbor, MI, Edited by M. Tigner, 1983, p.151.

6. K.Y. Ng, *Proc. 1986 Summer Study on the Physics of the Superconducting Super Collider*, Snowmass, CO, June 1986, p.590.

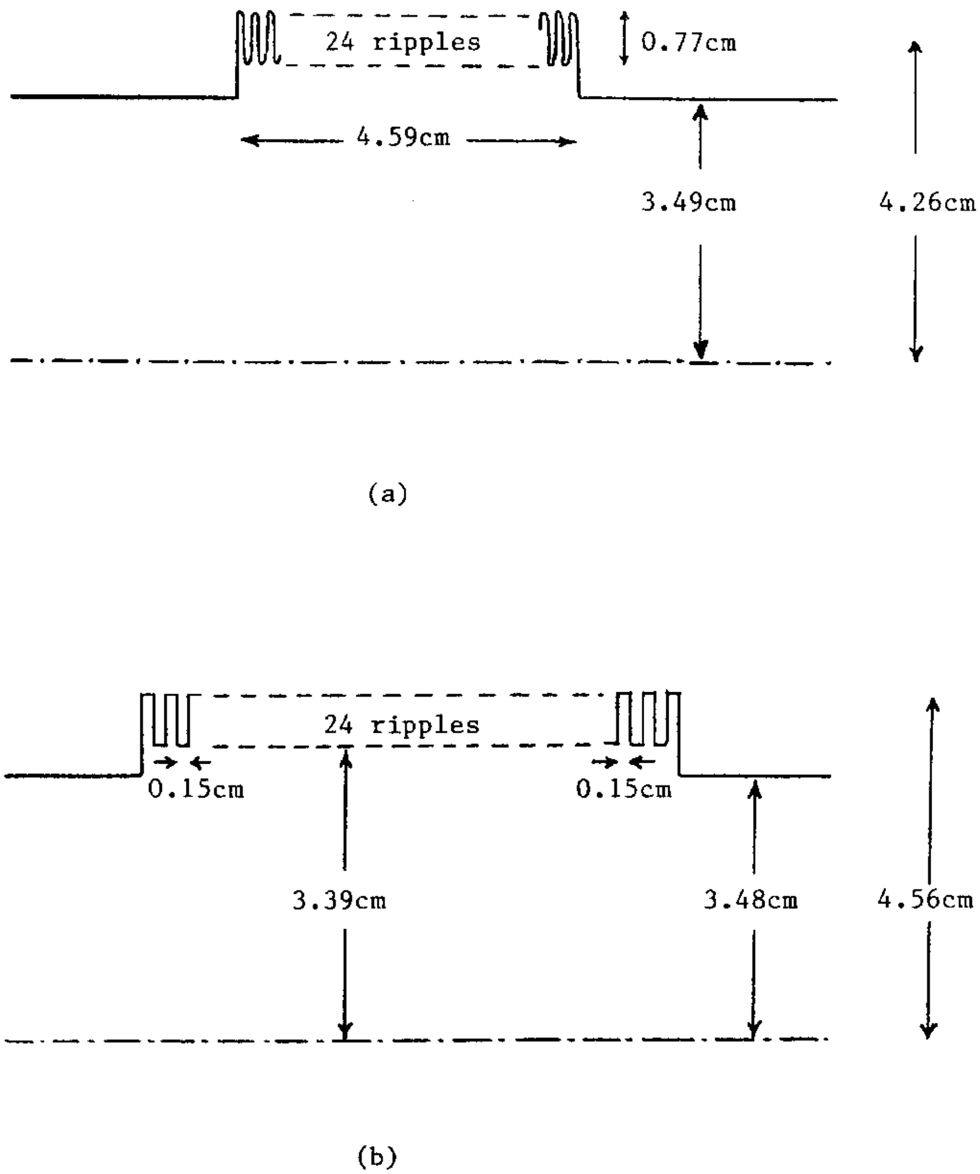

Fig. 1. (a) Dimensions of a Tevatron bellows at room temperature. (b) Dimensions of the Tevatron bellows at cryogenic temperature used in TBCI computations.

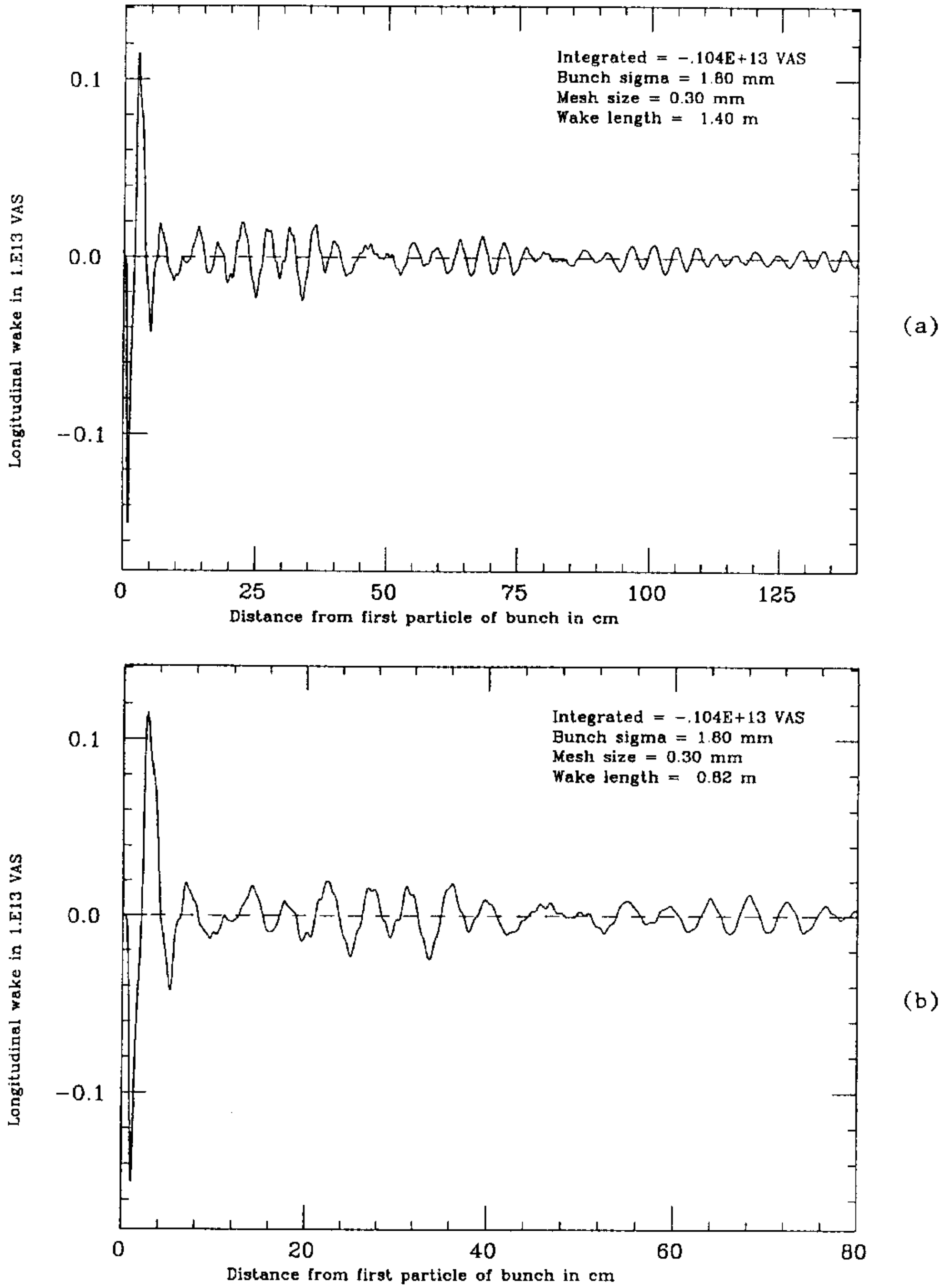

Fig. 2. (a) Longitudinal and (b) transverse wake potentials of a Tevatron bellows.

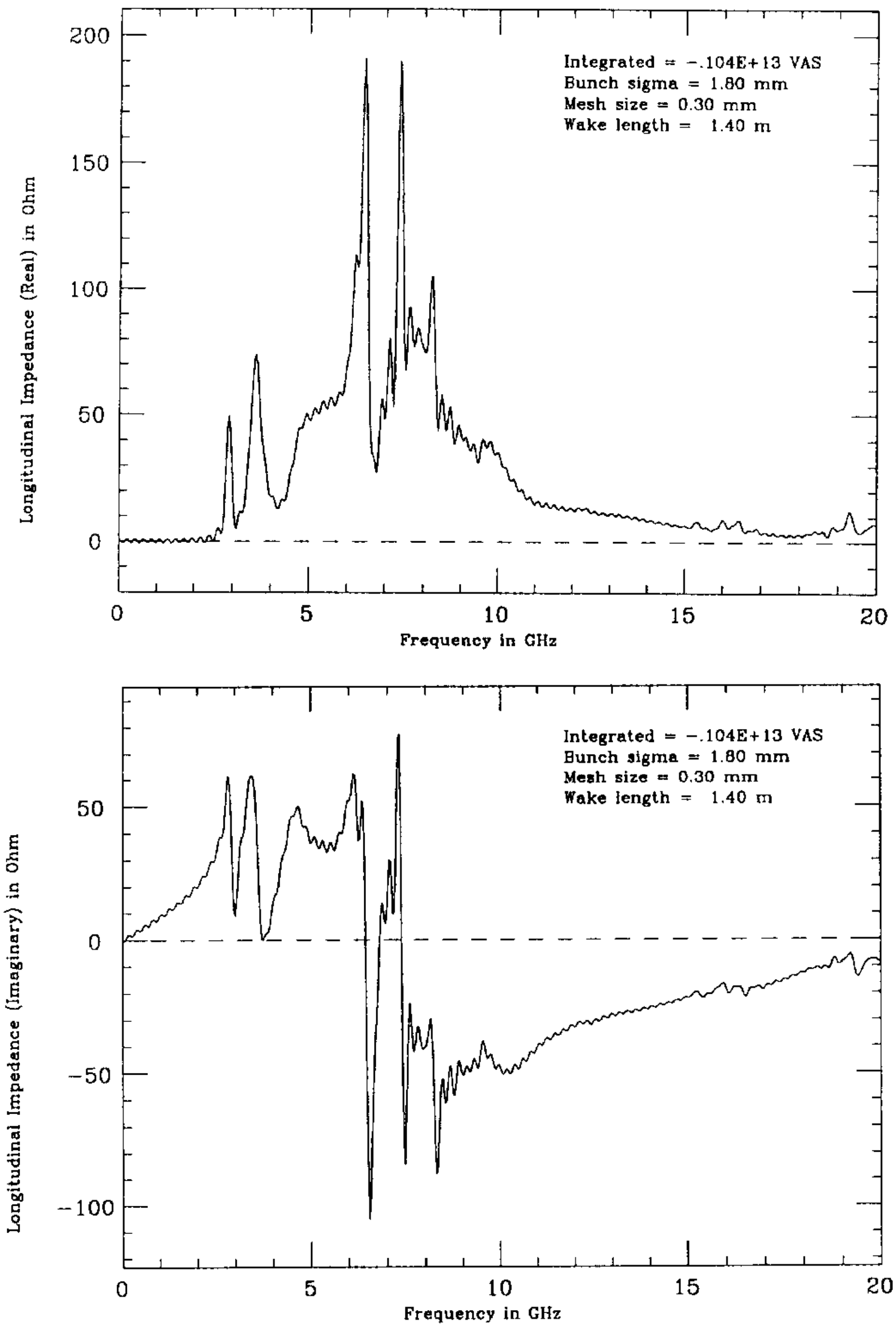

Fig. 3. Real and imaginary parts of the longitudinal coupling impedance of a Tevatron bellows.

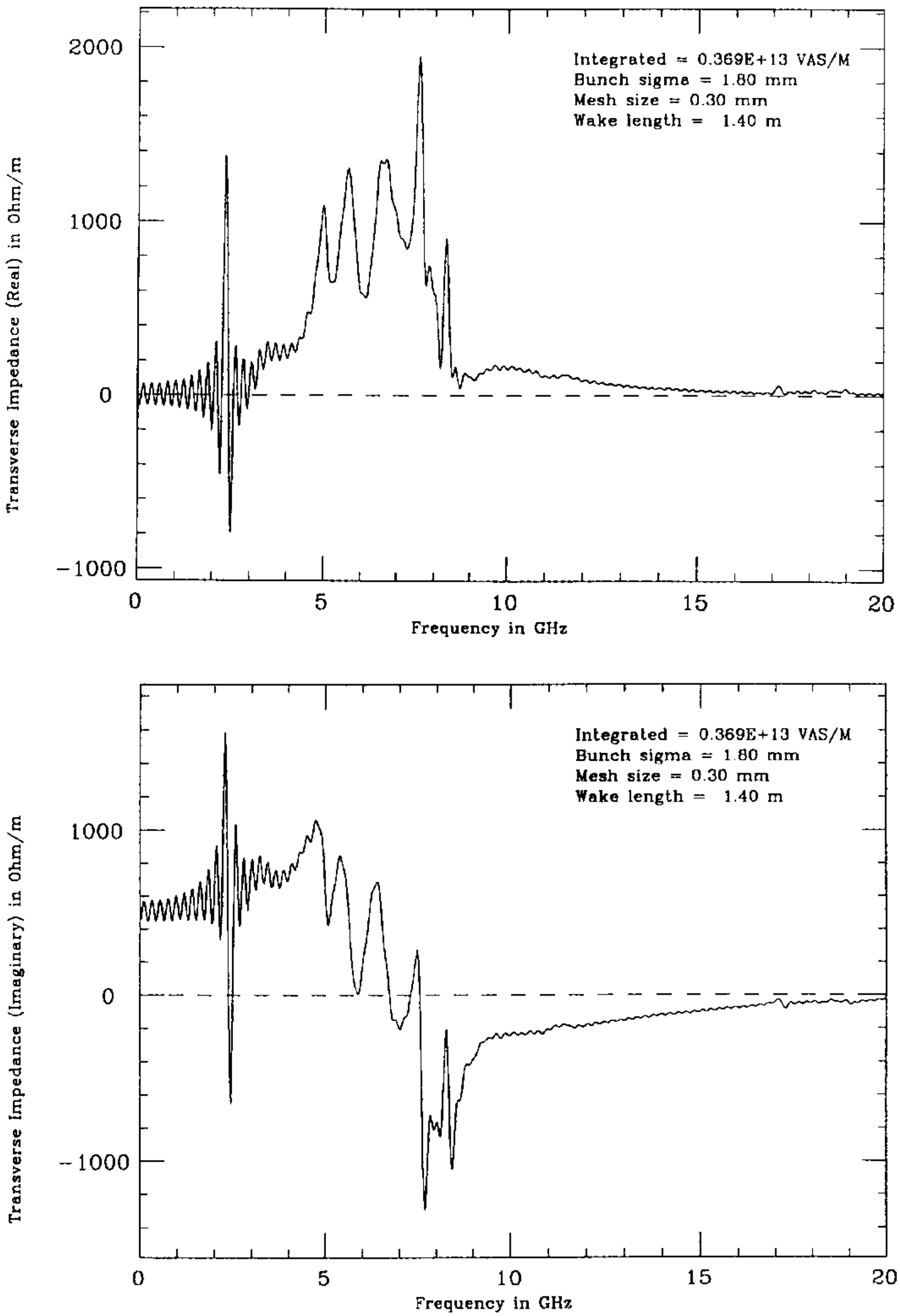

Fig. 4. Real and imaginary parts of the transverse coupling impedance of a Tevatron bellows.